HIGH RESOLUTION HOLOGRAPHIC CONTOURING

James W. Wagner

Center for Nondestructive Evaluation
The Johns Hopkins University
Baltimore, Maryland 21218

INTRODUCTION

Optical contouring techniques which incorporate holography have the potential for providing high resolution noncontacting topographic measurements of surface relief. In addition, holographic recording provides a means by which contour data may be archived indefinitely. Contouring may be applied to specular and optically rough surfaces and, through the use of pulsed holographic recording, may be applied where contour changes occur at very high speed.

Through the application of heterodyne holographic analysis[1], very high resolution contour data can be obtained. Increases both in sensitivity and dynamic range of 1000 fold over the corresponding homodyne techniques is possible. Heterodyne techniques also permit direct automated acquisition of contour data so that subjective interpretation of fringe patterns is no longer necessary. In addition, heterodyne holographic data can be collected without the directional ambiguity which accompanies visual fringe pattern interpretation.

Four optical full field contouring techniques to which heterodyne analysis may be applied will be considered: direct interferometry of specular surfaces, dual refractive index holographic recording, double wavelength holographic interferometry, and holographic fringe projection contouring. In the past, when it was desirable to apply heterodyne analysis to either of the three techniques for diffuse surface contouring, it became necessary to produce a double exposure dual reference beam hologram. A new technique called coherence multiplexing has been applied to the fringe projection contouring procedure in order that single exposure dual reference holograms may be recorded. With the need to record only a single exposure, the application of these techniques to high speed and high repetition rate contour recording is now greatly enhanced.

INTERFEROMETRIC CONTOURING OF SPECULAR SURFACES

Specular surfaces may be contoured in real time using traditional full field interferometric techniques. For such surfaces the application

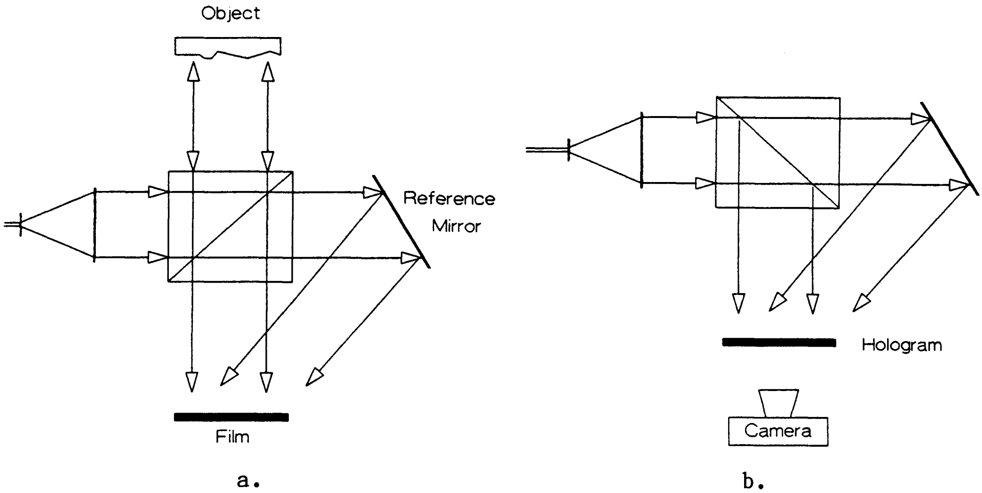

Figure 1. a) Recording and b) readout geometries for specular contouring.

of holography only provides a means by which the contour data may be archived. Thus the arrangement shown in Figure 1 appears very much like a standard Michelson interferometer. The hologram is recorded using the system diagrammed in Figure 1a and may be read out shown in Figure 1b. The hologram is reconstructed by the off axis illumination as shown and the object surface is compared directly with the expanded laser beam reflected by the beam splitter. The advantages of this technique include the fact that holographic contour data may be collected in a single holographic exposure and that sensitivity to surface displacement is the highest among all of the contouring techniques which will be described. However, the technique is not applicable for objects with optically rough, diffusely reflecting surfaces.

DUAL REFRACTIVE INDEX CONTOURING

The first technique to be considered for contouring diffusely reflecting object surfaces is one where a double exposure holographic recording is required. Using the recording scheme diagrammed in Figure 2, a holographic exposure is made with the object placed in a chamber filled with a fluid of known refractive index. A second exposure of the same holographic plate is made after the refractive index of the fluid within the chamber is changed by a small amount[2]. Upon development and reconstruction of the hologram, an image such as that observed in Figure 3 is obtained. The contour interval is a function of the wave length of the illuminating light and the change in refractive index of the fluid in the chamber as described by the equation below:

$$d = \frac{\lambda}{2(n_1 - n_2)} \tag{1}$$

In practice the chamber may be filled with air so that a change in refractive index may be obtained by changing the pressure within the chamber[3].

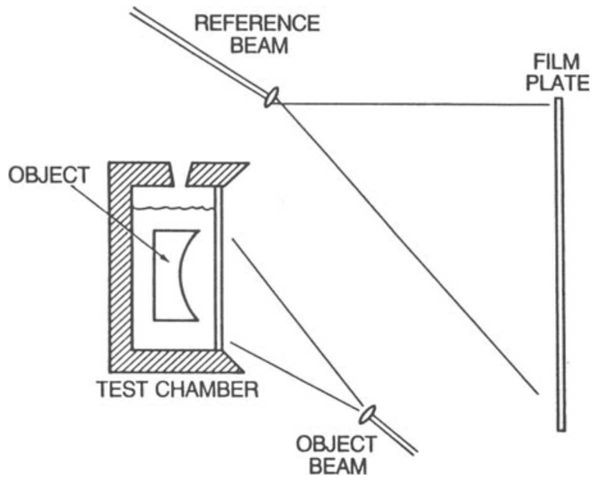

Figure 2. Dual refractive index contouring.

Figure 3. Contour of artificial knee component.

One advantage of using the dual refractive index technique is that diffuse object surfaces may be contoured. The sensitivity of the contour fringes is a variable which may be controlled by selecting appropriate differences in fluid refractive index. For reasons which later will become clear, the fact that the two images reconstructed by the hologram are in precise registry is also an advantage of this technique. The somewhat awkward implementation and need for independent calibration are unattractive features of this procedure. Further, the requirement for double exposure recording makes it difficult to apply this technique to high speed contour changes.

DOUBLE WAVE LENGTH CONTOURING

Double wave length holographic contouring is analogous to the dual refractive index technique in that a double exposure hologram is also recorded[4]. Rather than using a fluid a filled chamber, however, a double exposure hologram is recorded with a change in optical wavelength made between holographic recordings. Similar contour images are generated where the contour fringe sensitivity is as described in the equation below:

$$d = \frac{\lambda_1 - \lambda_2}{2\lambda_1\lambda_2} \tag{2}$$

The double wavelength technique has similar advantages to those of the dual refractive index technique. The sensitivity of the contour fringes is again variable and diffuse surfaces may be contoured. Unfortunately the technique suffers from alignment difficulties and also requires double holographic exposures.

HOLOGRAPHIC FRINGE PROJECTION CONTOURING

When two coherent beams of light intersect at a shallow angle, a series of interferometric fringes exists in the volume defined by their region of intersection. If an object surface is placed within the intersection volume these fringes are projected on the surface so that their lateral displacement is a function of the object surface relief. This procedure may be implemented holographically in order to provide data storage and to facilitate high resolution heterodyne analysis[5]. In its holographic form the two intersecting beams of light which would form a projected fringe pattern are used as separate object beams. That is, a double exposure hologram is recorded using first one object beam and then the other during the recording process. Upon reconstruction of the hologram an image such as that shown in Figure 4 is observed where one can clearly see the lateral deflection of the fringes as they describe the contour of the surface. Fringe sensitivity for this technique is described in the equation below.

$$d = \frac{1}{\cos\theta_1 - \cos\theta_2} \times \left[\frac{\cos^{-1}(2I-1)}{2\pi/\lambda} - x(\sin\theta_1 - \sin\theta_2) \right] \tag{3}$$

Where θ_1, θ_2 = Illumination angles

$I_{max} = 1$

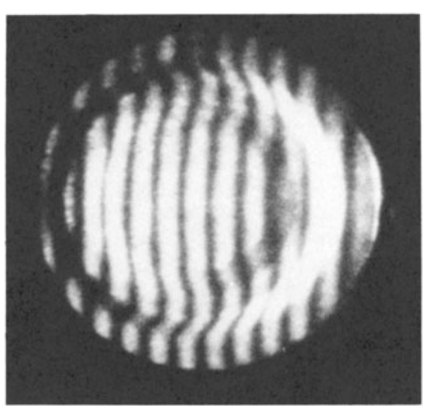

Figure 4. Fringes projected on a jar lid.

Holographic fringe projection, like the two previously described schemes, may be applied to diffuse surfaces, offers variable sensitivity, and produces precisely aligned reconstructed images. As will be shown shortly, through the use of coherence multiplexing, fringe projection holographic contouring can be performed with a single holographic exposure. For deeply convoluted surfaces this technique may suffer from shadowing of lower regions on the surface by higher areas.

HETERODYNE HOLOGRAPHIC ANALYSIS

All of the contour schemes described so far lend themselves to heterodyne analysis. With heterodyne interpretation of the holographic images, detailed information regarding surface contour may be obtained even between holographic fringes. Although many variations exist, the key to heterodyne analysis lies in the ability to manipulate the phase or frequency of one of the object images relative to the other during the readout process. For direct interference contouring of specular surfaces, one need change only the phase or frequency of the light illuminating the hologram, for example, in order to perform this type of analysis. In the other heterodyne holographic techniques however, the two recorded images must be encoded on the film using angularly distinct reference waves. Consider for example the scheme diagrammed in Figure 5. Note that two reference beams are drawn - one which is used when the film plate is initially exposed, and the second which is used during the second exposure after the refractive index of the fluid within the chamber is changed slightly. Figure 6 shows the results of reconstructing this hologram first with one, then the other, and finally with both reference waves. Notice that it is not until both reconstructing waves illuminate the hologram that the two object images 01 and 02 overlap and interfere. By imposing a relative change in phase or frequency between the reconstructing beams, one may shift the position of the fringes in the reconstruction. A series of static shifts in phase result in a corresponding series of holographic interference images which may be processed to provide measurement sensitivities approaching 1/100 of an interference fringe[6]. A continuous shift in phase, a frequency shift, results in a continuous motion of the fringes which may be detected using optical sensors as shown in Figure 6. One of the sensors is positioned at a reference location while the other sensor is scanned over the image plane. Mapping the phase difference between the phase difference between the electronic signals of the two detectors gives a direct measure of surface displacement and fringe position to nearly 1/1000 of a fringe[1]. This later technique of heterodyne holographic interferometry was used to produce the image shown in Figure 7 which presents the detail of one of the wear surfaces of an implantable artificial knee joint. Note the small gouge running the center of this contoured region. This gouge is not apparent at all from the stationary or homodyne interference image.

COHERENCE MULTIPLEXING

As pointed out above, the key to performing heterodyne analysis of holographic interferograms is the independent control of the two reconstructed images using angularly distinct reference and reconstructing waves. In general, the two reference waves are used in sequence during the recording of a double exposure hologram. With holographic fringe projection contouring, however, it has been shown that single exposure dual reference holograms may be recorded in order that high speed contour displacements may be studied. This has been

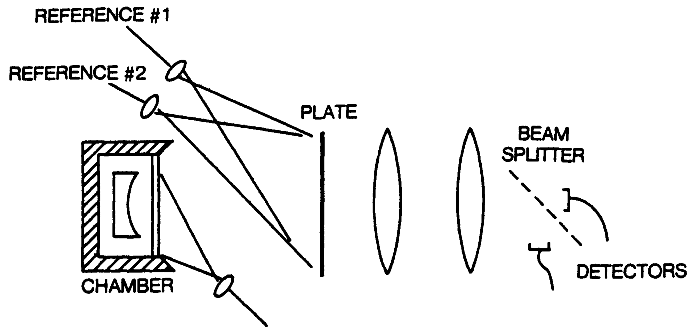

Figure 5. Dual refractive index holographic contouring using separate reference beams during recording.

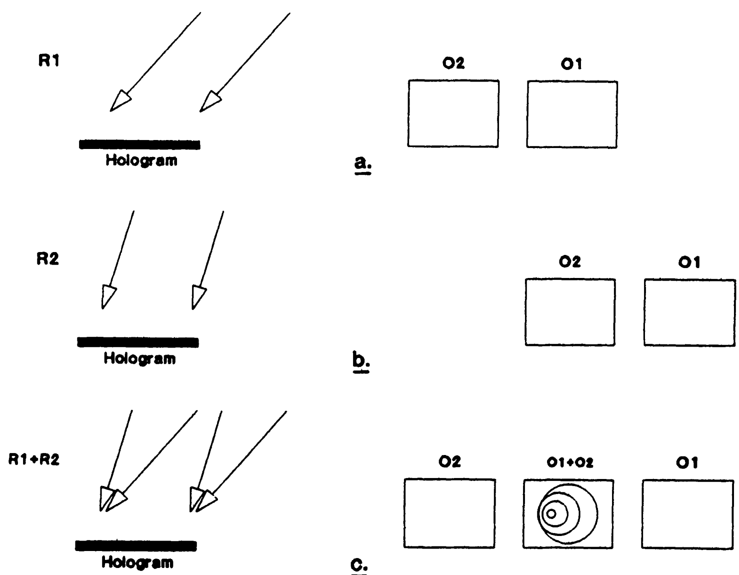

Figure 6. Holographic images are individually reconstructed (multiplexed) by corresponding reconstructing beams.

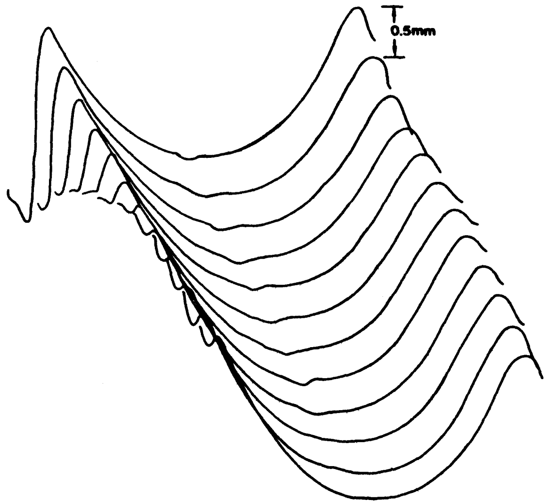

Figure 7. Heterodyne holographic contour mapping of artificial knee.

accomplished using a procedure known as coherence multiplexing. The recording scheme for this technique is shown schematically in Figure 8. A short coherence-length laser is used in the system, and propagation distances are adjusted so that mutual coherence exists between corresponding pairs of object and reference beams. That is to say that one of the object beams will interfere with only one of the reference beams during the recording process so that the information corresponding to the different illuminating angles is recorded separately on the hologram. During readout and analysis, the two reconstructing beam paths are made equal in length so that the reconstructed image wavefronts will interfere. The jar lid whose fringe projection image was shown in Figure 4 was contoured using this technique where a phase step (quasi-heterodyne) analysis was applied[6]. The results of this contouring process are shown in a wire frame plot in Figure 9.

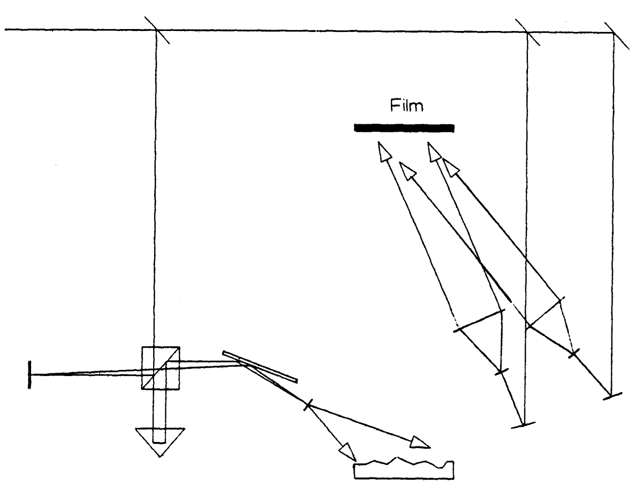

Figure 8. Coherence multiplexing for holographic fringe projection contouring.

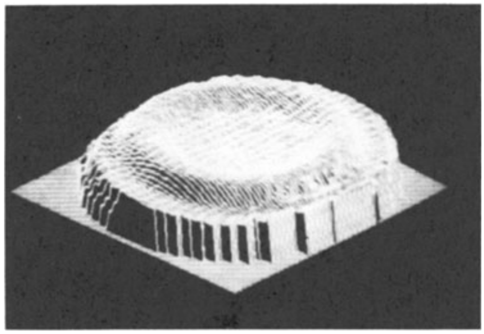

Figure 9. Wire frame display of jar lid obtained using quasi-heterodyne analysis.

CONCLUSIONS

It has been shown that holographic contouring, when coupled with heterodyne analysis techniques, may be used to provide high resolution contour mapping of specular and diffuse object surfaces. These combined techniques provide the further advantage of permitting automated analysis of surface contours while maintaining the raw data in an archival form on a hologram. A new technique called coherence multiplexing has been shown to permit single exposure dual reference holographic recordings. Coherence multiplexing facilitates high speed recording so that the dynamics of rapid contour changes may be studied with the sensitivity of heterodyne analysis. Contour sensitivities approaching Angstroms are possible using direct interferometric contouring of specular surfaces. Resolutions approaching 1/1000 of a fringe may be obtained using heterodyne analysis of the other holographic contouring techniques. Consequently, surface detail may be mapped to submicron accuracies.

ACKNOWLEDGEMENT

Work supported in part by the US Navy Office of Naval Research.

REFERENCES

1 Dandliker R, Heterodyne holographic interferometry, Progress in Optics 17, 1 (1980).

2 Zelenka JS, and JR Varner, Multiple index holographic contouring, Appl Opt 8, 1431-1434 (1969).

3 Wagner JW, Gardner DJ, Heterodyne holographic contouring for wear measurement of orthopedic implants, Proceedings of the International Congress on Applications of Lasers and Electr-Optics, Los Angeles, CA (November 1983), Laser Institute of America, Toledo, OH (1984).

4 Cathey WT, in Optical Information Processing and Holography, (Wiley, New York 1974) 332-335.

5 Thalmann R and R Dandiker, Holographic contouring using electronic phase measurement, Opt Engin 24(6) 930-935 (1985).

6 Hariharan P, Quasi-heterodyne hologram interferometry, Optical Engineering 24(4), 632 (1985).